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# Simultaneous regeneration of two 160 Gbit/s WDM channels in a single highly nonlinear fiber

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**Abstract:** We experimentally demonstrate simultaneous all-optical regeneration of two 160-Gbit/s wavelength-division multiplexed (WDM) channels in a single highly nonlinear fiber (HNLF). The multi-channel regeneration performance is confirmed by bit-error rate (BER) measurements. The receiver powers at a BER of  $10^{-9}$  are improved by about 4.9 dB and 2.1 dB for the two channels, respectively. The BER performance is not degraded by the presence of a second channel. Mitigation of the inter-channel nonlinearities is achieved through bidirectional propagation.

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## 1. Introduction

All-optical regeneration is a highly desirable functionality for high bit rate transmission based on high symbol rates, where the optical signal-to-noise ratio (OSNR) requirements become very strict [1]. It can potentially operate more power-efficient than optical-electrical-optical (OEO) regenerators at networks nodes. All-optical regeneration has been demonstrated using

different devices and materials, such as highly nonlinear fibers (HNLF), semiconductor optical amplifiers (SOA), periodically poled lithium niobate (PPLN) and silicon nanowires [2–7], among which the highest data rate for single channel regeneration achieved is 640-Gbit/s [5]. As most transmission today is based on wavelength-division multiplexed (WDM) systems, it would be beneficial if such a high speed optical regenerator could deal with WDM signals, but this has so far proven difficult. On the other hand, optical regeneration of an ultra-high bit rate channel may be achievable with low energy consumption.

In this paper, we demonstrate simultaneous all-optical regeneration of two 160-Gbit/s on-off keying (OOK) WDM signals using fiber optical parametric amplifier (FOPA) in a single highly nonlinear fiber (HNLF). The regeneration performance is validated by bit-error rate (BER) tests. Bidirectional propagation can mitigate the inter-channel interference, and the performance is not degraded by the presence of a second channel.

## 2. Principle

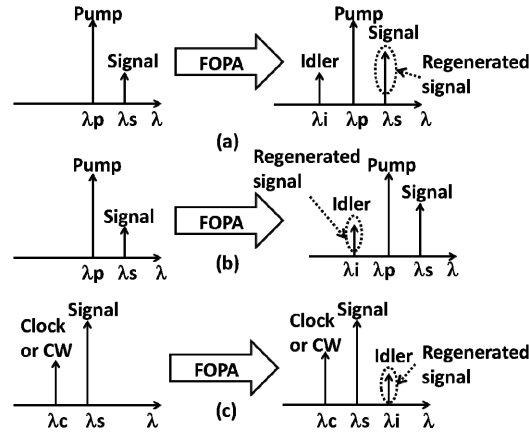


Fig. 1. Principles of regeneration using a FOPA. The principle used in this paper is (c).

Previously, FOPAs were often used for regeneration in the two schemes shown in Fig. 1(a) - 1(b). In both cases, the amplitude noise on '1' levels can be suppressed due to the gain saturation of the data signal or idler. However, the noise on '0' levels will be amplified. If the degraded data signal is applied as the pump as in Fig. 1(c), the obtained mixing product will exhibit significantly enhanced extinction ratio and noise suppression [8].

Here we focus on the Fig. 1(c) case, where the data signal is used as pump. When the data power is low ('0' levels), the amplifier gain of the idler wave is exponentially dependent on the data power [9]. Thus, the amplitude noise on '0' levels can be suppressed at the idler wavelength.

The noise suppression performance for data power at high power ('1' levels) is analyzed as follows.

According to [9], the phase-matching condition  $\kappa=0$  for a FOPA can be written in the form:

$$\kappa = \Delta k_M + \Delta k_W + \Delta k_{NL} = 0 \quad (1)$$

where,  $\Delta k_M$ ,  $\Delta k_W$ ,  $\Delta k_{NL}$  represent mismatches in propagation constants occurring as a result of material dispersion, waveguide dispersion and the nonlinear effects respectively.  $\Delta k_{NL}$  can be expressed as:

$$\Delta k_{NL} = \gamma(P_{clock} + P_{data}) \quad (2)$$

As the data power increases, the phase match will deteriorate by a nonlinear phase shift at high power. The gain of the idler wave will thus saturate. In this case, the amplitude noise on '1' levels can be suppressed. So in the Fig. 1(c) scheme, the amplitude noise on both '0' and '1' levels of the data signal can be suppressed at the same time.

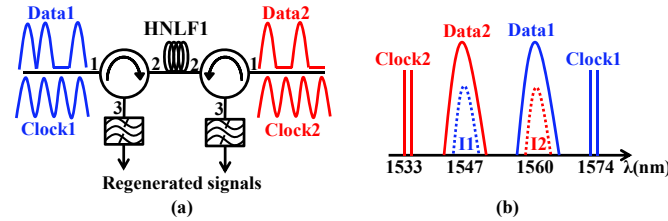


Fig. 2. (a) Scheme of the regenerator. (b) Wavelength position of the signals and clocks.

Figure 2(a) shows a schematic of the regenerator. A bidirectional scheme is adopted. Data1 and clock1 are fed into the HNLFI in the forward direction and data2 and clock2 in reverse direction. Circulators placed on both sides of the 200 m HNLFI are used to separate the counter-propagating signals in the fiber.

Figure 2(b) shows the wavelength allocation for the regenerator setup. Two counter-propagating data signals act as pumps for two clock signals, thus generating amplitude regenerated and retimed data replicas on the idler wavelengths. The wavelengths of data1 and data2 are 1560 nm and 1547 nm, and that of clock1 and clock2 are 1574 nm and 1533 nm, respectively. Note that, the regenerated data1 (I1) is at the same wavelength as data2 in this scheme (the same for I2 with data1). In this way, the regenerated WDM signals have the same bandwidth as before, but swap the wavelength position compared to the two input data wavelengths.

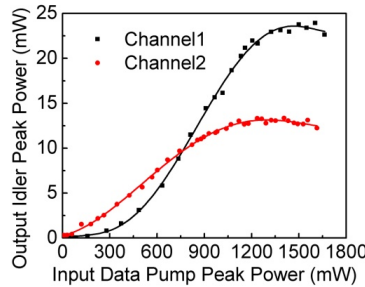


Fig. 3. FOPA transfer curves for the two channels.

Firstly, we measured the power transfer curves of the two FOPAs. The peak powers of clock1 and clock2 are fixed at 17.2 dBm and 21.2 dBm, which are optimized for the saturation of the FOPAs with different pump wavelength. As shown in Fig. 3, the exponential idler response of the FOPA at lower pump level allows for reducing the 0-level noise. For higher data pump power ('1' levels), the idler power saturates because of the nonlinear phase mismatch [9]. Thus, the noise on both '0' and '1' levels can be suppressed simultaneously.

### 3. Experimental setup

The experimental setup for the regeneration of the two 160-Gbit/s WDM channels is shown in Fig. 4. It includes the generation of the two data channels and two clock signals, a fiber based regenerator, an OTDM demultiplexer and a BER tester.

10 GHz short pulses with a full width at half maximum of 1.5 ps generated from a mode-locked laser (MLL) at  $\lambda = 1542$  nm are split into three parts. One part is used as the control

pulses for the OTDM demultiplexing. The other two are used to generate the two OTDM data signals and the two clocks. In the two-data signals generation unit, the 10 GHz pulse train is modulated with a pseudorandom bit sequence ( $2^{31}-1$  of PRBS). A 10-to-160 Gbit/s optical fiber-based multiplexer produces the 160-Gbit/s OTDM signal. The 160-Gbit/s OTDM signal is amplified by an Erbium-doped fiber amplifier (EDFA2), and then injected into a 400-m dispersion-flattened HNLF (DF-HNLF) (dispersion  $D = -0.45$  ps/nm/km and slope  $S = 0.006$  ps/nm<sup>2</sup>/km at 1550 nm, and  $\gamma = 10.5$  W<sup>-1</sup>km<sup>-1</sup>) to generate a supercontinuum. The supercontinuum is launched into a degradation sub-unit. Here, the supercontinuum is phase modulated with an asynchronous 2.5 Gbit/s PRBS ( $2^7-1$ ) signal. A 14-m DCF transforms the asynchronous phase modulation into random timing jitter. Amplitude noise is introduced by adding broadband amplified spontaneous emission (ASE) noise. The bias voltage of the data modulator is also adjusted to degrade the '0' level of the input data. After filtering in a wavelength selective switch (WSS), two degraded WDM signals at  $\lambda_{\text{data1}} = 1560$  nm,  $\lambda_{\text{data2}} = 1547$  nm are obtained. Note that only in-band ASE noise is added after the WSS.

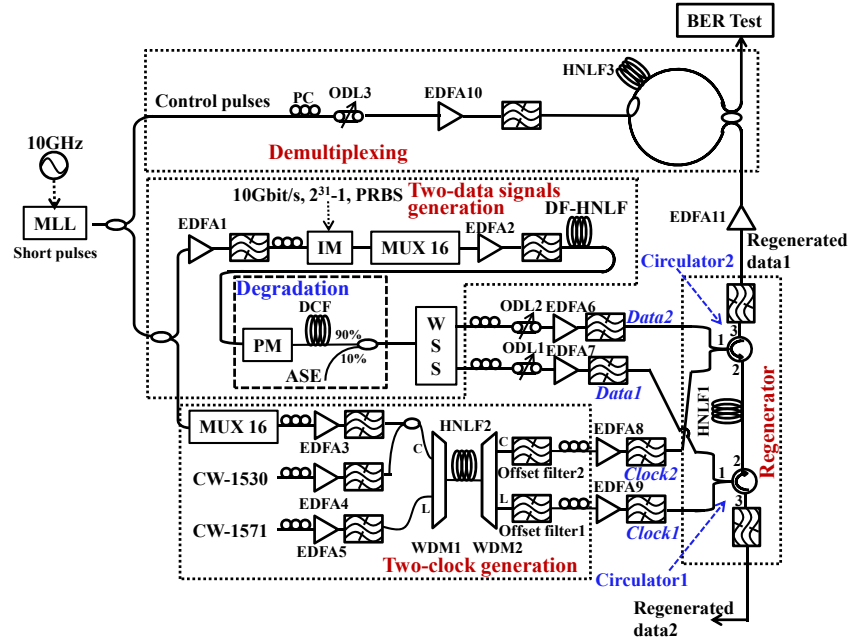


Fig. 4. Experimental setup of the regeneration of two 160-Gbit/s WDM signals.

The two-clock generation is based on cross-phase modulation (XPM) and two rectangular offset filters. A 10-to-160 GHz optical fiber-based multiplexer is used to produce a 160-GHz pulse train. The 160-GHz short pulses are amplified by EDFA3, and then launched into the 500-m HNLF2 (zero-dispersion wavelength at 1551.6 nm and slope  $S = 0.017$  ps/nm<sup>2</sup>/km at 1550 nm, non-linear coefficient  $\gamma = 10.5$  W<sup>-1</sup>km<sup>-1</sup>) through a coupler and a wavelength-division multiplexer (WDM1). Two continuous wave (CW) laser beams at 1571 nm (L band) and 1530 nm (C band) are launched into HNLF2 together with the 160-GHz short pulses. The spectrum of XPM for clock generation is shown in Fig. 5(a). At the output of HNLF2, another WDM (WDM2) separate the XPM spectrum into two parts (L band and C band). For each part of the spectrum, one rectangular filter at an offset of  $\sim 3$  nm is used to select two tones of the spectrum to generate the 160 GHz clocks. Since the optical sampling oscilloscope (OSO) can only measure C band signals, only the waveform of the generated clock at 1533 nm is shown in Fig. 5(b).

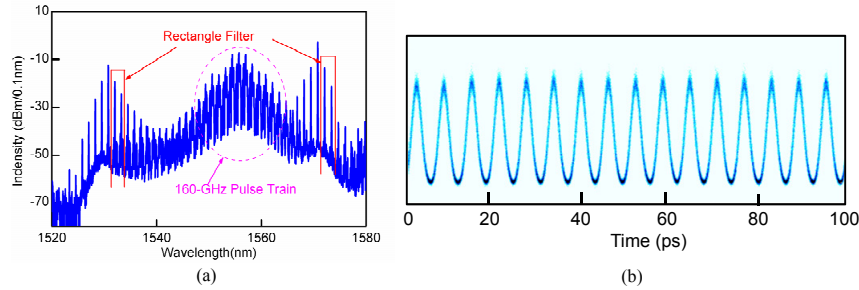


Fig. 5. (a) Spectrum of XPM for clock generation. (b) waveform of the clock at 1533nm.

In the regenerator, data1 is amplified by the high-power EDFA7. And clock1 is amplified by high-power EDFA9. One optical delay line (ODL1) is used to align data1 to clock1 when they are launched into HNLF1 (zero-dispersion wavelength at 1553.3 nm, dispersion slope  $S = 0.017 \text{ ps/nm}^2/\text{km}^{-1}$  and non-linear coefficient  $\gamma = 10.5 \text{ W}^{-1}\text{km}^{-1}$ ). The reflection coefficient of the HNLF1 is measured to be  $-32.5 \text{ dB/km}@1550 \text{ nm}$ , which is low enough to avoid the crosstalk resulting from the reflections of the counter-propagating signal [10]. Two circulators (The insulation from port 1 to port 3 is about 40~50dB) are used to separate the counter-propagating signals in the fiber. Data1 and clock1 are launched into HNLF1 through port2 of Circulator1. At the other side of HNLF1, the products of the parametric process by data1 and clock1 go into port2 of Circulator2. At port3 of Circulator2, the idler1 of the parametric process is filtered and the regenerated data1 is obtained. The same goes for data2 and clock2, and the regenerated data2 is obtained.

The following non-linear optical loop mirror (NOLM) is used to demultiplex the 160-Gbit/s regenerated signals down to a 10-Gbit/s signal. The NOLM operation is based on XPM in a 15-m HNLF3 (zero-dispersion wavelength at 1545 nm,  $S = 0.015 \text{ ps/nm}^2/\text{km}$  at 1550 nm, and  $\gamma = 10.5 \text{ W}^{-1}\text{km}^{-1}$ ). Finally, the demultiplexed 10-Gbit/s regenerated signal is detected by a 10-Gbit/s pre-amplified receiver and tested for BER.

#### 4. Results

The output power of EDFA7, EDFA9, EDFA6 and EDFA8 are 26.4 dBm, 22.3 dBm, 26.7 dBm and 26.6 dBm, respectively. Spectra at input and output of HNLF1 for channel1 and channel2 are shown in Figs. 6(a) and 6(b) respectively. The conversion efficiency of the FOPA at the two wavelengths is different, because of fiber dispersion [9]. 160-Gbit/s eye diagrams of the degraded and regenerated signals for Ch1 and Ch2 are shown in Fig. 7. There is a clear reduction of amplitude noise due to regeneration for both channels. The amplitude noises on both 0- and 1-levels are suppressed simultaneously.

The use of a sine-waveform clock allows for the re-timing capability of the regenerator [7]. The root-mean-square (RMS) timing jitter is improved from 240 fs to 170 fs (measured by an optical sampling oscilloscope, OSO) after regeneration for Ch1.

BER measurements for the two channels are shown in Fig. 8. The degradation of the signals causes an obvious error floor in the BER performance. Compared with the back-to-back (B2B) cases, the degraded Ch1 and Ch2 have a 5.9 dB and 2.7 dB receiver power penalty at a BER of  $10^{-9}$ , respectively. B2B here means the optimized 160-Gbit/s data signal demultiplexed to 10 Gbit/s, i.e. with no degradation added. After regeneration the error floor is notably suppressed and the receiver powers at the BER of  $10^{-9}$  are improved by 4.9 dB and 2.1 dB (for Ch1 and Ch2) respectively, being very close to those of the original B2B signals. The BER performance of the regenerated Ch2 with Ch1 ON is quite similar to that with Ch1 OFF, indicating there is almost no cross-talk between the two channels in the HNLF1.

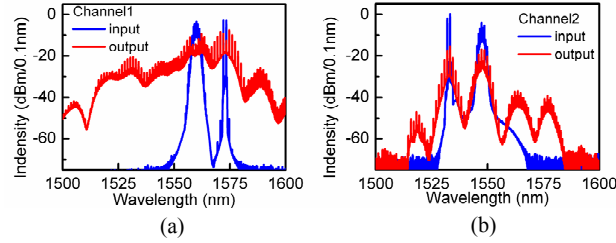


Fig. 6. (a) Spectra at input and output of HNLF for Ch1. (b) Spectra at input and output of HNLF for Ch2.

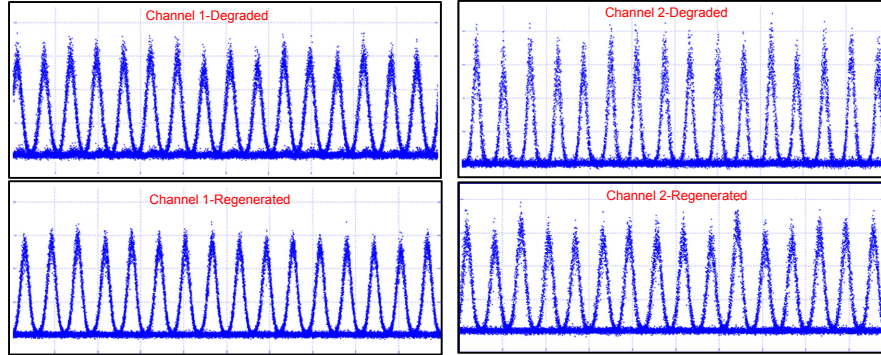


Fig. 7. 160-Gbit/s eye diagrams of degraded and regenerated signal for Channel 1 and Channel 2.

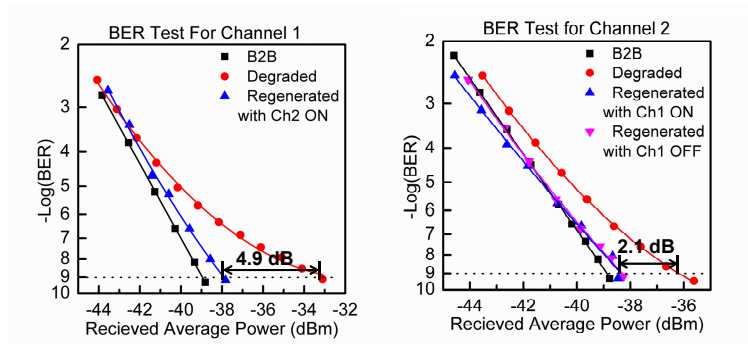


Fig. 8. 10-Gbit/s BER performance after demultiplexing for Ch1 and Ch2.

## 5. Conclusion

We have experimentally demonstrated simultaneous all-optical regeneration of two 160 Gbit/s OOK WDM signals based on bidirectional propagation in a single HNLF. In the regeneration using a FOPA, the data signals act as pumps enabling simultaneous 0- and 1-level noise suppression. The receiver powers at  $10^{-9}$  are improved by 4.9 dB and 2.1 dB for channel 1 and channel 2 respectively. The BER performance shows the cross talk between two-channel regeneration is negligible. Note that, the scheme presented in this paper is not applicable to phase shift keying signals due to the data pumps, which could not make the phase information maintained in the idler wavelengths. Our scheme could also be scaled to four WDM channels with polarization and direction multiplexing. An inter-channel 0.5 bit slot time delay can minimize cross talk between the co-propagating polarization-multiplexing two channels [11].



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